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VACUUM SYSTEM FOR PROTON STORAGE RINGS EQUIPPED WITH SUPERCONDUCTING MAGNETS

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1. INTRODUCTION

Considerable attention has been devoted, in the last few years, to the vacuum behaviour of Proton Storage Rings, both in order to overcome the difficulties encountered during the operation of an existing machine (ISR at CERN)[1-5] and to decide the design characteristics of future machines (Isabelle[6-8] and ESCAR[9-11]).

The experience gained on the ISR clearly demonstrates that the vacuum is an important parameter in achieving the design performance: on the one hand, the pressure increase due to ion bombardment of the vacuum chamber walls can destroy the circulating proton beams, and on the other hand, all available information leads to the conclusion that an average pressure in the low 10^{-11} torr range is desirable. Although these vacuum requirements are now clear and we have learned how to fulfill them in the particular case of the ISR, the solutions adopted in the latter machine could not be simply applied to a machine like POPAE for at least two reasons; first: the aperture of the vacuum chamber needed for higher energy machines is smaller; second: the presence of superconducting magnets offers the possibility of cooling the vacuum chamber to liquid He temperature. The first reason implies that in order to maintain a reasonable safety margin from the vacuum stability point of view (see next paragraph) the distance between the pumping stations should be small, with a corresponding increase of the total length of a machine (or decrease of the "packing factor") and therefore of the capital cost for a given proton energy and magnets. This inconvenience could disappear when cooling the vacuum chamber to about 4.5K because the vacuum chamber itself would then provide the necessary pumping. Furthermore, the aperture of the vacuum chamber could possibly be reduced even further, if desired for the fabrication of the magnets. Finally, the initial cleanliness of the vacuum chamber would become much less critical and the expensive and time-consuming cleaning procedure might even be abandoned.

However, no experience is available on the vacuum behaviour of a cold wall machine, and "a priori" it is not obvious that it will permit the circulation of proton currents of reasonable intensity.

The purpose of this note is to explore the possibility of a "cold-bore" solution in the light of the available information and with respect to the various aspects of the vacuum problem.

2. STATIC AND DYNAMIC PRESSURES - VACUUM STABILITY

2.1 General

The gas molecules present inside the vacuum chamber and ionised by the circulating protons are accelerated by the electrostatic field created by the proton beam and bombard the surrounding walls. This bombardment results in a desorption of molecules and/or trapping of the impinging ions. If we define η as the net number of molecules entering the gas phase, negative η values indicate that the number of trapped ions exceeds the number of the desorbed molecules ($\eta = -1$ if all the ions are trapped and no molecules are released). In this case the pressure in presence of beam (dynamic pressure) is lower than the pressure in absence of beam (static pressure). If the number of desorbed molecules exceeds that of trapped ions η is positive and the beam produces a pressure increase. No intrinsic limitations exist for positive η; the actual value depends on the chemical composition of the bombarded walls, on the nature, concentration and binding energy of the gases there present, and on the energy and mass of the impinging ions. It can be shown analytically[3] that for a given vacuum system in presence of a circulating beam of intensity I, a critical value $(\eta I)_{crit}$ exists above which the pressure runs away and the beam is lost. This critical value is proportional to the effective pumping speed per unit length of vacuum chamber[3,8]; higher circulating beam intensities can therefore be obtained by reducing η and/or by increasing the effective pumping speed.

2.2 Warm vacuum chamber

For the ISR vacuum system the calculated $(\eta I)_{crit}$ values range from 40 to 100 approximately[3], depending on the distance between the pumping stations and the conductance of the interposed vacuum chamber. Values of η ranging from -0.5 to 4 have been observed corresponding to various materials, surface treatments and beam intensities. For a vacuum chamber of smaller conductance, for example a cylindrical cross section with 60mm diameter, and a distance of 5 m between pumping stations, $(\eta I)_{crit}$ would amount to 10, i.e. for I=10 A only η values below 1 are acceptable[8]. At the present level of knowledge it is impossible to guarantee that a machine many kilometers long and characterised by η lower than 1 over all its length can be built. In order to keep a reasonable safety margin the maximum distance between adjacent pumping stations should be about 3 m, and many thousands of them would be required for a machine like POPAE. Any future improvement in the direction of obtaining, reliably, very small or even negative η values can obviously modify these considerations.

2.3 Cold vacuum chamber

2.3.1 Vacuum stability

A completely different situation appears when considering a cold vacuum chamber (say at 4.5K). On the one hand, the chamber itself presents now a pumping action (molecular adsorption pumping, not to be confused with the ionic pumping of the beam, which can be present also if the vacuum chamber is warm) which results in increased values of pumping speed per unit length of vacuum chamber and therefore increased values of $(\eta I)_{crit}$; on the other hand the cold surfaces can adsorb large quantities of weakly bound gas molecules with the consequence of increasing η. Since η values as high as 5×10^4 have been measured[12,13] and a $(\eta I)_{crit}$ equal to 1.8×10^4 has been calculated[8], the cold solution does not seem at first glance to provide any stronger guarantee of vacuum stability. Looking more deeply into the problem, we will now try to critically review the information available or the ways of estimating η and the pumping speed of the cold chamber, which, alone, define I_{crit}.

The only existing experimental η values for gases adsorbed at liquid He temperatures have been obtained at Culham Laboratory[12,13]. The desorption yields per impinging ion (5KeV hydrogen ions) have been measured as a function of the condensed gas concentration for Argon, N_2 and CO (Cu condensing surface at 4.2K) and for H_2 and He (Cu condensing surface at a temperature between 4.5 and 2.5K). All the gases behave in a similar way: η increases, linearly in first approximation, with the surface coverage up to about 3×10^{15} molecules/cm^2 (according to the experimental evidence obtained in our laboratories this coverage corresponds to the completion of the first monolayer) and then decreases, more quickly for the heavier gases than for H_2 and He. The peak values of η are of the order of 100 for Argon, N_2, CO and about 5×10^4 and 10^4 for H_2 and He respectively. When H_2 is condensed at 2.5K on top of a precondensed Argon layer, η is practically the same as on bare metal i.e. 5×10^4 for H_2 surface concentrations above a monolayer. For coverages of the order of a few monolayers η falls to about 10 for the heavier gases, while about 100 monolayers are necessary before an appreciable decrease is observed for H_2.

Note that in all these experiments the bombarding particles were hydrogen ions and that higher η values could possibly be obtained when bombarding with heavier ions (N_2, CO for example). Therefore, these data could rigorously be used only for estimating a pure H_2 situation.

However, even for H_2, the η values measured in a laboratory experiment should not be confused with the effective values η_{eff} which will be encountered in practice inside a Storage Ring vacuum system. These two ηs are correlated by the following equation:

1) $$\eta_{eff} = \eta(\theta\varepsilon + \alpha\theta n)$$

where η is the yield, measured for bombarding H_2 ions of 5KeV and a concentration of the considered gas of 3×10^{15} molecules cm^{-2};

θ is the actual coverage in units of 3×10^{15} molecules cm^{-2} (we consider here only $\theta < 1$)

ε is a factor describing the dependence of η upon the energy of the impinging ions;

α is the fraction of the desorbed molecules which are energetic enough to further desorb $\underline{n}$ molecules from a complete monolayer.

Very little is known about ε: the only available information is that [12], for H_2, η shows practically no change when the energy of the bombarding H_2 ions is raised from 5 to 20KeV. This fact shows that the desorption process reaches saturation before 5KeV, and, since in Storage Rings the energies of the bombarding protons usually range between 1 and 2KeV, $\varepsilon = 1$ represents an upper limit to the possible ε values. We will therefore assume $\varepsilon = 1$ and this is certainly a pessimistic statement. α and n depend on the energy spectrum of the desorbed molecules (not known) and on the energy dependence of the desorption yield, which is only partially known: the experience gained in our laboratories on condensed H_2 (the most critical gas in this respect) shows that H_2 molecules of energies up to 3×10^{-2} eV (gas molecules at 300K) are practically unable to desorb other H_2 molecules condensed at 2.3 - 4.2K. No information is available above this energy; however, a simple energy balance shows that only a small fraction of the desorbed molecules could have higher energy. Assuming a desorption energy for H_2 (adsorbed on a metal surface) of 5×10^{-2} eV and 3×10^{-2} eV kinetic energy per molecule, 5×10^4 desorbed molecules would require 4KeV. In a practical case, where the bombarding ions have an energy below 5KeV, η must be lower than 5×10^4 and/or the kinetic energy of the desorbed molecules lower than 3×10^{-2}eV. We therefore neglect the second term in the bracket and 1) simply becomes

$$2) \quad \eta_{eff} = \theta\eta$$

In other words, the effective desorption yield is assumed to be proportional to the measured yield, and the multiplying factor is just the actual gas coverage of the vacuum chamber in the particular situation.

From the equations describing the dynamic pressure situation inside the vacuum chamber[3] and neglecting the effect of the pumping stations, the following equation has been obtained[8]:

3) $(\eta_{eff} I)_{crit} = \frac{\pi}{15} r \bar{v} s$

where I is expressed in Amperes, $\bar{v}$ is the arithmetic mean velocity in cm/s, r the radius of the vacuum chamber in cm and s the sticking probability for the molecules hitting the walls of the vacuum chamber. Assuming s = 1, r = 4cm and $\bar{v} = 14551 \sqrt{\frac{T}{M}}$ with T = 4.5K, it follows[8]:

4) $(\eta_{eff} I)_{crit} \simeq 1.8 \times 10^{4}$ for H_2

5) $(\eta_{eff} I)_{crit} \simeq 4.7 \times 10^{3}$ for N_2

However, the equation 3) has been obtained by assuming an ionisation cross section $\sigma = 1.2 \times 10^{-18} cm^{2}$, which is valid for nitrogen gas[3,4]. The corresponding value for hydrogen, to be used for the equation 4) is about a factor of seven smaller[10]. By correcting and combining with 2) we have:

4*) $(\theta I)_{crit} \simeq 2.6$ for H_2 ($\eta = 5 \times 10^{4}$)

5*) $(\theta I)_{crit} \simeq 50$ for N_2 ($\eta = 100$)

For N_2, $\eta = 100$ represents the peak value, and the peak is very narrow. On the other hand, the quoted η values have been obtained by bombarding N_2 gas adsorbed at 4.2K with hydrogen ions, while in the case of a N_2 pressure bump the bombarding ions will be N_2. The situation described by 5*) is therefore not too well defined, but clearly less critical than the H_2 situation described by 4*). In the case of H_2 for 10A circulating current a H_2 surface concentration of about 0.3 only (or 10^{15} molecules cm^{-2}) is allowed for stable operation.

Here again the estimation is affected by the lack of knowledge of the energy distribution of the desorbed molecules because both $\bar{v}$ and s depend on it. However, the above estimation must be considered pessimistic for the following reasons. When increasing the energy of the desorbed molecules s decreases from 1 (which is a good approximation up to about 30K) to about 0.7 and 0.5 at 77K and 300K respectively, for clean metal surfaces[14]; for surfaces partially covered with H_2 the corresponding s values are higher. For the same energy increase $\bar{v}$ increases much more, because it follows the square root of the temperatures of the molecules (rigorously if s = 1, and in an attenuated way for lower s, due to the energy accommodation at the first collision with the cold walls). As a result, the pumping speed increases with increasing energy of the molecules. For example, if the molecules have an energy corresponding to 30K, the increase of the pumping speed will be about 2.6.

2.3.2 Static pressure

The vacuum stability is not the only pressure requirement: other reasons dictate that both the static and the dynamic pressures must be below a value which, for a H_2 atmosphere and room temperature operation, is of the order of 3×10^{-11} torr (i.e. approximately the real average H_2 pressure in the ISR now). Due to the variation of the gas density with the temperature and to the fact that the gas density and not the pressure determines the gas-beam interaction rate, a working temperature of 4.5K implies that the H_2 pressure should not exceed about 4×10^{-13} torr. For all the gases except H_2 and He the vapor pressures at 4.5K are well below 10^{-15} torr, therefore their equilibrium pressures in the present application will always be negligible. For H_2, at this same temperature, the vapor pressure is in the 10^{-6} torr range. However, the formation of the first monolayer, in the absence of thermal radiation, and if H_2 is adsorbed on a clean metal surface, is characterised by an equilibrium pressure below 10^{-13} torr[15,16]. If the metal surface is already covered by a H_2 monolayer or by a layer of a better condensable gas (we have information for Ne and Argon) the addition of about a tenth of a monolayer of H_2 is already enough to raise the pressure above 10^{-12} torr.

A similar situation is achieved for a quantity of below 10^{-3} of a monolayer of He adsorbed at 4.2K on a metal surface[17], but He is usually absent from an all-metal vacuum system, and this case will be considered later.

2.3.3 Dynamic pressure

A possible way of estimating the dynamic pressures below the critical situation, as well as the critical surface coverages, consists in comparing the pumping and desorbing rates for the unit surface area. We will limit our considerations to the case of H_2 because this case is the most critical both from vacuum stability and static pressure points of view.

If we assume that at 10^{-9} torr one circulating proton produces 0.2 ions per second in a H_2 atmosphere at room temperature[4,10], remembering that at 4.5K the molecular density for a given pressure is 70 times higher, the number of ions bombarding per second a cm^2 of vacuum chamber wall will be:

$$6) \quad \frac{0.22 \times 10^{9} \times 70 \text{ P N}}{\text{L S}}$$

where P is the H_2 pressure at 4.5K, N the number of circulating protons in a machine of length L, and chamber circumference S.

Since each ion desorbs $\eta\theta$ molecules, the number of the molecules desorbed per second and cm^2 is:

$$7) \quad \frac{0.22 \times 10^{9} \times 70 \text{ P N}}{\text{L S}} \times \frac{\eta\theta}{70 \times 3.5 \times 10^{19}}$$

expressed in torr liters of H_2 gas at 4.5K.

On the other hand, the amount of gas pumped per cm^2 is:

8) $5.4\ (1 - \frac{Po}{P})\ P$

where 5.4 is the pumping speed, in liters per second, of a cm^2 of vacuum chamber for H_2 gas and assuming a gas temperature of 4.5K and sticking probability 1. (i.e. under the pessimistic assumptions previously discussed). P_o is now the static equilibrium pressure and the term in brackets indicates that the available pumping speed vanishes when approaching the static pressure.

The critical situation is obtained when, by increasing θ, the term in 7) exceeds the maximum possible value of the term in 8), which is 5.4 P for $P >> P_o$. In this case the pumping can not remove all the desorbed gas and the pressure runs away. For values of θ below this critical situation, the dynamic equilibrium pressure can be obtained by equating the two terms in 7) and 8). The equality can always be restored, when varying θ, by the factor in brackets in 8). Note that the dynamic pressure will be stable in the present case, while in the case of the ISR it decays due to the presence of external pumps, which continuously remove gas from the vacuum chamber.

If we now consider a machine like POPAE, for example, with $L = 9 \times 10^5$ cm, S = 25cm (80mm diameter circular vacuum chamber) and 1.5×10^{15} circulating protons (10 Amperes beam intensity), we obtain $\theta_{crit} = 0.26$, i.e. exactly the same value obtained [see equation 4*)] in a different way but under the same assumptions.

As far as the dynamic equilibrium pressure is concerned, from 8) it follows that for coverages equal to 80% of the critical value $P \sim 5P_o$ only. Since P_o for submonolayer coverage is well below 10^{-13} torr, the dynamic pressure practically does not introduce any important restriction on the maximum permitted θ.

2.4 Recapitulation of the discussion

Coverages of the order of 10^{-3} of a monolayer only (or 3×10^{12} molecules /cm^{-2}) of He are allowed, if no other gases are present on the walls, because for higher coverages the static pressure exceeds the required figure of 4×10^{-13} torr[17]; if other gases are present, even lower He coverages are allowed, but taking special precautions the presence of He can be avoided (see section 4). For H_2 on clean metal the lower limit of θ_{crit} has been estimated to be about 0.3; the tolerable value is certainly higher because we have chosen pessimistic values both for η and $\bar{v}s$. Always for H_2 on clean metal surfaces, the static and dynamic pressure requirements can be satisfied for coverages of above 0.8 of θ_{crit}. If a monolayer or more of another gas is present on the walls the static pressure requirements limit the H_2 concentration to below 0.1 of a monolayer.

All the stability conditions and dynamic pressure considerations can easily be transformed for circulating beam intensities and vacuum chamber diameters other than 10 A and 8cm respectively, because θ_{crit} is inversely proportional to the circulating current intensity and directly proportional to the vacuum chamber diameter.

2.5 Estimation of θ and preliminary conclusions

The problem of estimating the vacuum behaviour of a cold machine is therefore reduced to estimating the H_2 coverage of the walls as a function of the vacuum cycle. The simplest cycle consists in pumping down the vacuum system without baking, at room temperature, and then cool to 4.5K. In this case a few monolayers of water vapour are present on the walls, thus H_2 coverages of only a few hundredths of a monolayer are permitted. We do not see any possibility of estimating the initial H_2 concentration in this situation, but in any case the water will certainly dissociate under ion bombardment and a few monolayers of H_2 are potentially always present. We feel that this situation is too dangerous and that, furthermore, this choice does not represent an interesting simplification (see section 4) and therefore it should not be taken into consideration.

A bake (initially at 300°C for example) of the vacuum chamber will remove the gases present on the walls, and their final coverage will depend on the pressure and temperature situation during the bake-out cycle. The experience gained with the ISR only permits us to state that η values lower than 4 can be achieved by keeping the pressure low during the bake-out cycle. In the particular case of a cold vacuum chamber the distance between the pumping stations could be considerably greater and the diameter of the vacuum chamber considerably smaller than in the case of the ISR. The pressures during the bake-out cycle will therefore be higher, and so also the final surface coverage, but with the information now available the latter quantity can not be calculated. However, information is available in the form of adsorption isotherms and, for H_2 only, the infra-red radiation induced desorption of molecules from surfaces at liquid He temperatures[15,16]. The latter effect is characterised by a desorption yield, and therefore a sensitivity, which is much lower than ion or electron induced desorption, and cannot provide information if coverages of the order of 10^{-2} or lower are considered. However, the extensive investigations carried out in our laboratories on isotherms of H_2 adsorbed on various substrates in the temperature range between 2.3 and 4.4K and under various infrared radiation loads provides all the desired information for coverages above about 0.1. More precisely, experimental evidence exists that exposure of a metal surface at a temperature above 77K to any H_2 pressure, and subsequently repumping to below 10^{-8} torr, produces a final coverage lower than 0.1. Since in a practical case these extreme conditions will never be reached and since the critical coverages discussed above are higher than 0.3, we conclude that the cold solution is safely applicable to Proton Storage Rings. More particularly, in the case described by 4*), putting $\theta = 0.1$, it follows that currents up to 26 A are allowed for stable operation.

2.6 Nota

Even if the surface concentrations are assumed to be definitely higher than the critical value for given intensity and diameter, we still think that the cold solution could be feasible by properly designing the vacuum chamber. For example, if a structure similar to that shown by the Fig. 1 is adopted, the outer wall will cool before the inner shield, and by adjusting the thermal contact between them the final gas concentration on the inner shield could be kept as low as in the ISR. The situation on the outer wall would not then be critical (only the inner shield would be bombarded) except in so far as the static pressure is concerned, and θ could be as high as 1. The outer wall would act as an external pump also in presence of circulating beams, and provide a pumping speed per meter of chamber of the order of a few thousand liters per second for H_2 at 4.5K. The dynamic pressure would therefore now decay due to the progressive displacement of gas from the inner to the outer wall. For example, the amount of H_2 corresponding to $\theta = 10^{-2}$ could be displaced in about one minute at a pressure of about 10^{-10} torr (H_2 pressure at 4.5K).

Although the vacuum stability requirements are seemingly satisfied by means of the simple cold tube, we think that this more complicated structure is of more than academic interest, because the inner shield could have other important functions and might well be adopted for other reasons. As an example, a part of the inner shield, if electrically insulated, could provide a continuous clearing of the electrons produced by the beam; furthermore, the shield could provide a trouble free baking facility when heated up by Joule effect.

3. PUMPING STATIONS, PRESSURE MEASUREMENTS AND DEFINITION OF THE VACUUM SECTORS

The pumping stations placed at both ends of the cold sectors should consist of a turbomolecular pump (TM), a sputter ion pump (SP) and a Ti sublimation pump (SU). The TM (about 100 $\ell\ s^{-1}$ pumping speed) will insure the forepumping in the main vacuum system and in protecting vacuum regions (see section 4). The SP pump (about 200 ℓ s^{-1}) will provide the pumping during the bake-out and for He in case of leaks. Finally, the function of the SU pump will be to reduce the pressure on the pumping station to below 10^{-11} torr, in order to reduce the H_2 inlet to the cold sectors and, at the same time, increase the sensitivity for leak detection (He is not pumped by the SU pump, and smaller leaks will be detectable if the background pressure is lower).

On the pumping station a total pressure ionisation gauge for pressure measurements down to the 10^{-12} torr range and leak detection should be mounted. Inside the cold sectors and in presence of beam the pressure may be measured by means of the clearing current. According to 6) at a pressure of 4×10^{-13} torr (H_2 at 4.5K) and for 10 A circulating beam the clearing current will be about 1.5×10^{-9} A per 10m length of vacuum chamber. The sensitivity of this clearing current "gauge" is therefore perfectly adequate to detect pressure increases in the 10^{-13} or 10^{-12} torr ranges. Wherever more local pressure indications and/or higher sensitivity are desired, electron multipliers can be placed on the vacuum chamber in such a way that they are reached by the ions ejected by the beam. If the active surface of such a multiplier presents an area of $4 cm^2$ the counting rate will still be 40 pulses per second at a pressure of 10^{-17} torr. The background produced by stray radiation around the machine can be discriminated by biassing the first dynode of the multiplier in such a way that positive ions are rejected.

The vacuum system of big machines must be subdivided in sectors in order to limit the amount of work involved when an intervention on one of its parts becomes necessary. The obvious choice for a sector in the present case is the cold section between two pumping stations, i.e. a sector valve should be mounted at both ends of a cold sector (see Fig. 2). These valves should permit independent interventions on any cold sector or pumping station or combination of the two. The length of a sector will be determined by the more restrictive condition between He losses during the bake-out and the frequency around the machine of components which can not be cooled to liquid He temperatures (see section 5.2).

4. LEAKS AND LEAK DETECTION

The leaks always represent a problem for any vacuum installation, and the problems become extreme for large Storage Rings; particularly if the cold solution is adopted, because of the additional thermal stresses due to the cooling. Since a single leak can stop the machine for times of the order of a few days, depending on its importance, position and required interventions, we think that any effort directed to minimise the trouble is justified even if it results in additional complication of the vacuum system, and therefore higher fabrication cost. The problems and the possible solutions for the warm and the cold parts of the vacuum chamber are different and we will treat them separately.

4.1 Cold vacuum chamber

The vacuum chamber in the magnet regions could consist of a stainless steel tube of 4 to 8cm diameter cooled to 4.5K over lengths of the order of 100m. Let us assume that the cold chamber be immersed in liquid He inside dewars containing at least a dipole magnet or, possibly, 2 or 3 dipoles and a quadrupole. If a leak opens up, He gas will enter the vacuum chamber and the pressure will quickly deteriorate to levels above the maximum permitted. No chance then exists of repairing, because the chamber is not accessible; the sector must then be warmed up, opened to air, and, after having localised the leak with respect to the He dewars, the corresponding dewar must be dismantled and the leak repaired. The complication of this intervention is such that this possibility should not be considered even if the leak probability is extremely small.

A relatively simple way of overcoming the problem consists in protecting the vacuum chamber with a second concentric wall, and in keeping the so-formed annular region under vacuum (obviously, some mechanical complications will arise where the presence of special pieces of equipment imposes a change of cross section and where the dewars join each other). However, if this annular region is simply sealed off under vacuum, this solution presents two disadvantages: first, the cooling time of the vacuum chamber would be extremely long; second, the situation in the annular region is out of control, i.e. leak detection is not possible. We rather propose a solution where the pressure in the annular region may be varied according to the operating necessities and independently for chamber sections of the length of a He dewar. When a sector must be cooled, He gas at atmospheric pressure would be subsequently introduced in these annular regions. During injection a pressure increase on the total pressure gauge mounted on the nearest pumping station will reveal the presence of a leak. If a leak appears the corresponding region will be reevacuated and kept under vacuum until an intervention for repairing becomes possible. The cooling of the corresponding piece of vacuum chamber will be insured, in the meantime, by thermal conduction along the vacuum pipe from the two adjacent dewars.

After cooling, the thermal losses on the inner vacuum chamber will, alone, decide upon the necessity of leaving He gas in the annular region. For coasting, debunched beams (as in the case here considered) the only heating introduced by the beam comes from the lost protons, and this heating is certainly negligible with the possible exception of the stacking period. However, even assuming that during this period 10% of the protons are lost all around the machine the resulting heating is negligible. Therefore He gas need only be present in these regions during the cooling. If a leak opens during this time, the result is not a catastrophy. As a matter of fact, helium gas sticks to the walls only at temperatures below about 20K; the initial wall cleanliness could therefore be restored by simply heating a cold sector to this temperature (after having evacuated the He from the annular regions) while pumping with ion pumps. The leak detection procedure described above may then be applied.

If bunched beams and acceleration in the rings are to be considered, the currents induced in the chamber walls by the beams and the eddy currents produced during the acceleration would require a permanent thermal contact between the two walls, in order to keep the inner wall cold, and this solution would then become much less attractive. However, the thermal contact could be ensured in this case by mechanical means; for example, a ribbon of pure aluminum or annealed copper wound around the inner tube and compressed between the inner and the outer tubes. The ribbon should be wound in a spiral to permit the evacuation of the annular regions; the possibility of injecting He gas is then also conserved for leak detection purposes.

This alternative presents the disadvantage that if the vacuum chamber is vented to atmospheric pressure the magnets must automatically be warmed up to room temperature; furthermore, during the bake-out, the magnet temperature would follow quite closely the temperature of the vacuum chamber (see section 5). We therefore conclude that this solution should only be applied when a permanent thermal contact is absolutely necessary.

4.2 Warm vacuum chamber

The ISR experience shows that at least 90% of the leaks appear on the flange joints. The flanges should therefore be replaced by Argon arc welds wherever possible; only gauges, pumps, feed-throughs and valves should be flanged on the vacuum chamber. The importance of a leak varies depending upon whether it appears on the pumping station (region A in Fig. 2) or behind the sector valve, before the beginning of the double wall protection (region B in Fig. 2). In fact, a pumping station can be easily opened to air, with the sector valves closed, for the repair of a leak and then rebaked in a few hours. If, on the contrary, the leak appears in region B of Fig. 2 the cold sector must be opened to air, and the intervention will then take a much longer time. The flanges of region B must, therefore, also be surrounded by a protective vacuum. However, we suggest that all flanges be protected in this way, for example by using a double seal with intermediate pumping. If this solution is adopted the remote leak detection, described for cold chambers, could be extended to practically all the machine vacuum components, including pumping stations and warm experimental regions.

5. CRYOGENIC IMPLICATIONS OF THE VACUUM SYSTEM GEOMETRY AND OPERATION

The thermal losses in the magnet regions, during operation, are estimated to be roughly 3 W per meter of machine[18]. These losses are expected to come, in equal proportions, from the vacuum chamber, He dewar and electrical leads of the magnets. The refrigerators necessary for a machine like POPAE must supply at least 40KW at 4.5K in operation and some extra power for the cooling. However, when a vacuum intervention on the machine is being carried out, about 20% of the steady state cooling power will be available because the magnets will not then be powered and therefore the losses through the magnet electrical leads will be greatly reduced. We will therefore adopt the strict requirements that the losses introduced by the vacuum system are much smaller than 1 W per meter in operation and lower than 8 KW when a simultaneous intervention is carried out on two vacuum sectors.

The latter requirement is based on the assumption that all the cooling capacity in excess in the machine can be concentrated on the sectors where an intervention is carried out. For practical reasons this could be impossible, and we will also consider the extreme case where each sector is fed solely by its own refrigerator, and this refrigerator is dimensioned for steady state operation. An increase in losses will then be followed by an increase in temperature up to the level where the corresponding cooling power, which increases with the temperature, will be high enough to establish thermal equilibrium. In this case a warming up to 20 - 30K is certainly tolerable, because, due to the small heat capacity of metals at these temperatures, the further recooling will be extremely quick. Since the cooling capacity will then correspondingly increase by about a factor of six, a similar increase can be tolerated for the losses during an intervention.

5.1 Steady state operation

At each end of a cold vacuum sector, radiation and conduction losses are present. Considering that two black cavities (at 300K on the pumping station and 4.5K for the cold chamber) are coupled at these points, 45mW per cm^2 of chamber cross section will enter the cold region. Assuming a chamber diameter of 8cm the total radiation inlet per cold to warm transition will be about 2 Watts, and therefore negligible with respect to He consumption. However, this radiation is enough to yield a H_2 equilibrium pressure in the 10^{-13} torr[16] for coverages of the order of θ_{crit} and under the assumptions that the vacuum chamber is made out of stainless steel and that the radiation is homogeneously adsorbed on the walls of a sector 100m long. The regions nearest the pumps will certainly adsorb more radiation than the others and they will also present higher H_2 coverages due to the degassing from the warm steel; a particularly critical situation could therefore appear at these transition regions. In order to overcome this problem a black baffle at liquid N_2 temperature should be mounted in these regions.

5.2 Replacement of a liquid He dewar

Figure 3 shows a possible connection for the vacuum chamber between dewars. The protecting double wall may be the magnet bore and heating facilities need to surround the vacuum chamber (inner tube) for baking. The connection can be made by welding at A the lips of the vacuum chambers belonging to the two different dewars and by protecting the volume V around A with rough vacuum and superinsulation. The lips in A can be designed in such a way that they provide the elasticity needed to compensate the thermal expansion of the vacuum chamber.

The volume V is independent of the two adjacent annular protecting regions, and can similarly be pumped or filled with He gas for leak detection. All the necessary feed-throughs and pieces of equipment which could leak, or for any other reason must be accessible, should be grouped in this region.

If a magnet is to be replaced or, for any reason, a dewar removed, the vacuum chamber of the complete vacuum sector must be warmed up to 300K before being vented, together with the volume V, to atmospheric pressure with dry Nitrogen gas. The volume V can then be opened up, the vacuum chambers disconnected and the new dewar inserted as previously described. All the vacua are subsequently restored and the vacuum chamber finally baked to only 150°C.

During this intervention the magnet bore is kept cold and the annular regions under vacuum. The radiation exchange between the two concentric surfaces will depend on their geometrical dimensions and emissivities: for tubes of 6 and 8cm diameter out of polished stainless steel (emissivity 0.1) the losses will be 4.5 and 18W per meter at room temperature and 150°C respectively; these figures can be reduced to about 1 and 3.5W per meter if the two facing surfaces are Silver plated[16].

The thermal conduction is reduced by the presence of the bellows b1 and b2 (see Fig. 3). When considering a bellows presenting 75 and 95mm inner and outer diameters, wall thickness 0.1mm, 5 convolutions per cm and a length of 10cm, the resulting losses between 150°C and 4.5K are of the order of 10^{-1}W per bellows, and therefore completely negligible.

From these calculations it clearly appears that in the worst case (150°C and surfaces not Silver plated) a sector of about 100m length will require about 2KW, and that 4 such sectors could be simultaneously baked if all the cooling power available during the intervention can be concentrated in this area. Alternatively, two sectors 200m long could be handled. If each sector is fed by an individual refrigerator, in the worst case above considered, the temperature of the magnets will increase to about 30K and the length of the sector becomes independent of vacuum considerations. We conclude that all the vacuum interventions can be carried out without warming up the magnets to room temperature. In addition, the limitation of the sector length due to vacuum considerations is 200m in the worst case.

Obviously, if the magnets are at room temperature, higher baking temperatures (up to 400°C if desired) are possible, although we do not think they are necessary in the "cold bore" situation.

6. CONCLUSIONS

The pressure requirements (static, dynamic and stability) can be fulfilled by a "cold bore" vacuum system for ratios of the circulating current intensity (in Amperes) to the vacuum chamber diameter (in cm) below 3. This statement is based on experimental information already available and is certainly pessimistic.

The cold part of the machine should be subdivided in sectors of a length up to 200m, the actual length being possibly determined by the necessity for pieces of equipment which can not be cooled to liquid He temperature.

Leaks in the cold regions can be handled by means of a double-walled vacuum chamber structure; this also permits a quick and remote leak detection. In the warm regions and pumping stations the leak problem might be solved in a similar way if double-seal flanges are used; and we think that this point deserves further development.

The replacement of a magnet dewar, as well as the subsequent bake at 150°C is possible with the magnets kept cold. Pressure indications in the cold regions can be obtained, in presence of beam, by measuring the clearing current or by counting the ions reaching electron multipliers placed on the side of the vacuum chamber. The clearing electrodes can have a continuous structure or be placed at the ends of the magnet dewars; the first solution presents the advantages of a more efficient clearing, a more compact machine structure, and increased safety from the pressure point of view; the disadvantages are a bigger magnet bore and a more complicated vacuum chamber.

The proposed cold bore solution appears to be far cheaper than the alternative warm because of the higher packing factor (around 0.8; the actual value depending on the length of the cold sector and on the choice of the He dewars). There is also a saving of about 97% of the traditional pumping stations and of about 30% of the necessary cooling power (no losses from the cold vacuum chamber during operation).

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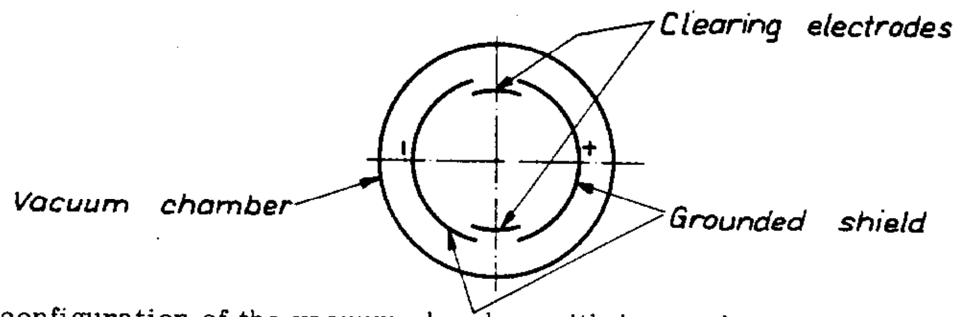
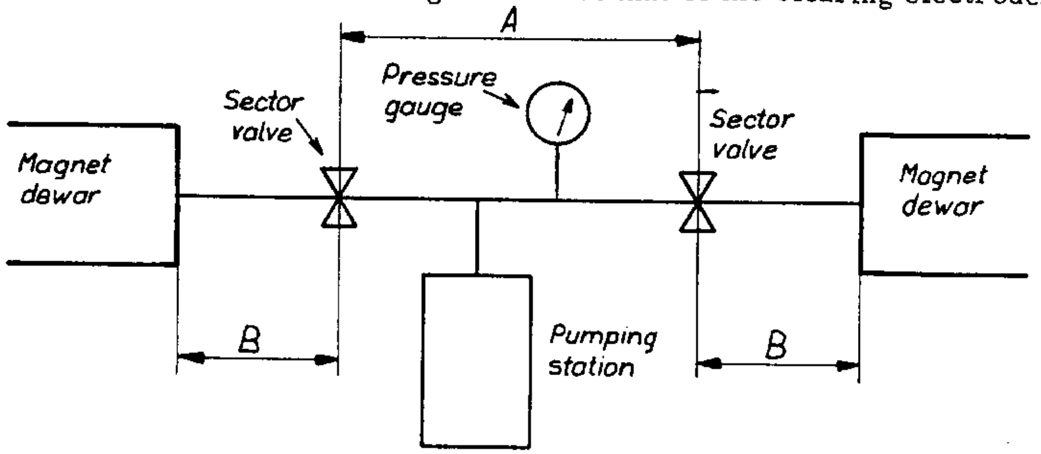
Fig. 1

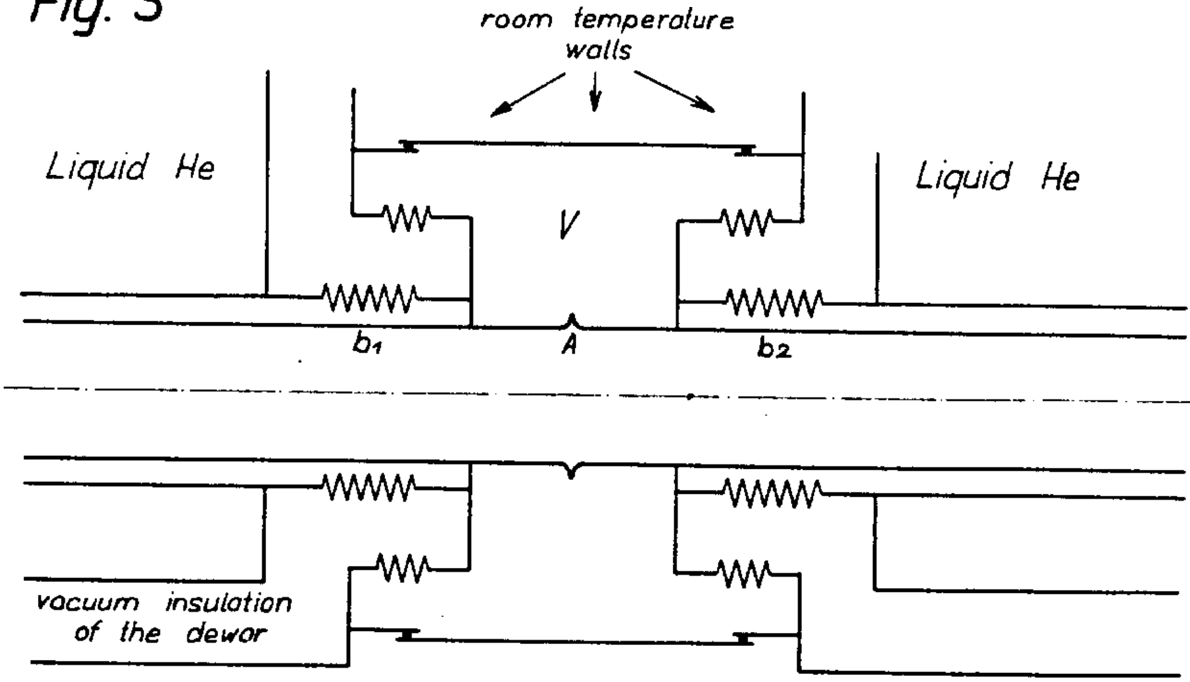


Possible configuration of the vacuum chamber with inner shield. The clearing electrodes will be bombarded by high energy electrons, which however are about 10 times less effective than protons in desorbing H_2. In order to obtain equal equilibrium coverages with and without beam the grounded shield surface area should therefore be about 10 times greater than that of the clearing electrodes.



Pumping station, sector valves and cold sectors.

Fig. 3



Possible connection between magnet dewars.